Development of a Precise Magnetic Field Measurement System for Fast-Changing Magnetic Fields

Peter Wanderer, John Escallier, George Ganetis, Animesh Jain, Wing Louie, Andrew Marone, Richard Thomas

***Abstract*—Several recent applications for fast ramped magnets have been found that require precise measurement of the time-dependent fields. In one instance, accelerator dipoles will be ramped at 1 T/sec, with measurements needed to the typical level of accuracy for accelerators, $\Delta B/B$ better than 0.01%. To meet this need, we have begun development of a system containing 16 stationary pickup windings that will be sampled at a high rate. It is hoped that harmonics through the decapole can be measured with this system. Precise measurement of the time-dependent harmonics requires that both the pickup windings and the voltmeters be nearly identical. To minimize costs, printed circuit boards are being used for the pickup windings and a combination of amplifiers and ADC's for voltmeters. In addition, new software must be developed for the analysis. The paper will present a status report on this work.**

***Index Terms*—fast magnetic field measurements, non-rotating pickup coil, printed circuit boards**

I. INTRODUCTION

MAGNETIC field measurements of nearly all accelerator magnets are made with systems designed for constant or slowly-varying fields. Measurements of multipoles are commonly made with rotating coils that have a period of several seconds [1]. Recently, we have encountered a need for measurements of fast-ramped fields in magnets for three different projects. A significant upgrade has been approved for the accelerator facility at Gesellchaft für Schwerionenforschung (GSI) in Darmstadt, Germany. The upgrade will include two superconducting synchrotrons that will ramp at dB/dt 1-2 T/s [2]. A model fast-ramp dipole has been built and operated at this ramp rate at BNL by a BNL-GSI collaboration [3]. BNL is exploring whether the Alternating Gradient Synchrotron (AGS) can be ramped at high rates so that a next-generation neutrino beam can be produced [4]. Also at BNL, a model magnet that will generate orthogonal 0.4 T dipole fields using two cos-θ windings has been built and ramped successfully at rates of several Hz. Magnetic field measurements are needed to test whether the field can track the motion of small mammals, such as a rat [5]. If so, a magnet like this could be used inside a 4 T NMR solenoid to potentially allow scans of awake animals. (At present, NMR scans can only be made on sedated animals.) For each of these magnets, it is important to measure all the low-order harmonics.

In certain instances, measurements of the time variation of specific harmonics (e.g., the normal sextupole) have been made with specialized systems. For example, a coil sensitive to a single multipole, such as the sextupole, can make measurements at a few Hz. Such devices are of interest for measuring the time-dependent behavior of the sextupole in superconducting accelerator magnets. Limitations on coil rotation speed and signal sampling prevent its use for the systems described above.

A non-rotating coil with multiple probes can be used to make measurements at higher rates. For example, a system of three Hall probes can be set up to measure the sextupole. However, careful intercalibration of each probe is necessary, and nonlinearities limit the accuracy of the device. A system of multiple pulsed NMR probes has been successfully used in DC magnets, but measurements of rapidly varying multipoles have not been demonstrated [6,7]. Furthermore, such a system is significantly more complex as compared to search coils, and can only be used for homogeneous fields, such as dipoles with good field quality.

II. GENERAL APPROACH

We are developing a harmonic coil array for measuring fast-ramped magnets. Printed circuits are relatively inexpensive and reproducible, and will be used for the windings. Sixteen printed circuits will be mounted as tangential coils on a cylinder. We are sampling terms as high as the 16-pole, with the goal of obtaining reliable measurements at least as high as the decapole. The 16 probes will be intercalibrated by rotating the coil in a reference dipole field. However, the coil will be stationary when used for measuring fast-ramped fields.

The voltage will be sampled at rates as high as 50 Hz. The voltage sampling system must also cover a wide range of signal amplitudes and allow for frequent calibration and DC

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offset checks.

In the stationary mode, the total flux seen by a given probe is determined by its angular position, as well as the multipole components of the field. The angular profile constructed with voltage signals from various probes is, in general, not a Fourier series. In order to simplify the analysis, it is essential that the geometric parameters of various probes be as identical as possible, and the probe angular positions be as uniformly spaced as possible (see Sec. V).

III. PRINTED CIRCUIT PROBES

We have designed a 10-layer printed circuit board with six turns per layer for a total of 60 turns. The lines on the circuit boards are 0.1 mm wide and have 0.1 mm gaps between them. The circuit boards are 0.3 m long and the average width of the pattern is 11.6 mm. Fig. 1 shows the probe array assembled for the bio-med magnet and a detail of one of the printed circuit ends. The boards are 1.7 mm thick and the effective radius of the cylinder on which the probes are mounted is 35.7 mm.

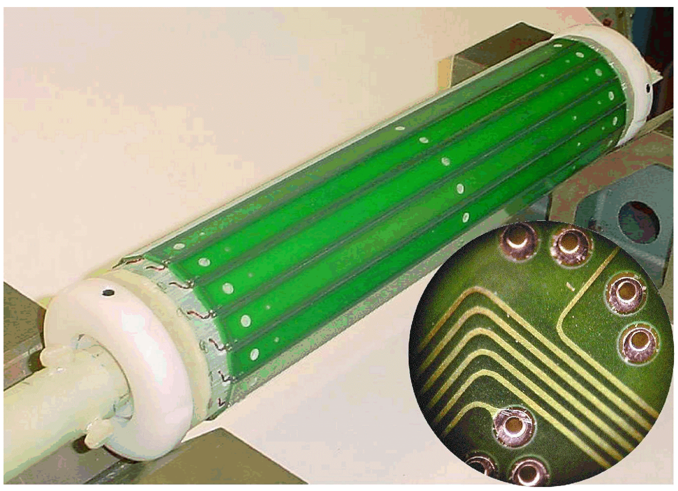

Fig. 1. Array of 16 printed circuits mounted on a cylindrical coil form. The inset shows the detail in a corner.

A. Probe Inspection

Several parameters have been measured for inspection of the printed circuits: probe resistance, probe inductance, and voltage generated in a ramped dipole field. Careful and efficient inspection was necessary because a significant fraction of the probes had turn-to-turn shorts. In principle, probes with turn-to-turn shorts can be identified by measuring the resistance of each one. However, experience showed that the variation of the resistance of the probes themselves was large enough to mask shorted turns. This is primarily because even small differences in the copper thickness can produce a relatively large percentage change in the resistance. Inductance measurements were found to be a much more reliable indicator of the total probe area. This can be seen in Fig. 2, where there is a clear separation between GSI probes with L ~ 1.13 mH and those with L < 1.10 mH. (These probes have not yet been checked in a dipole field, as described below.)

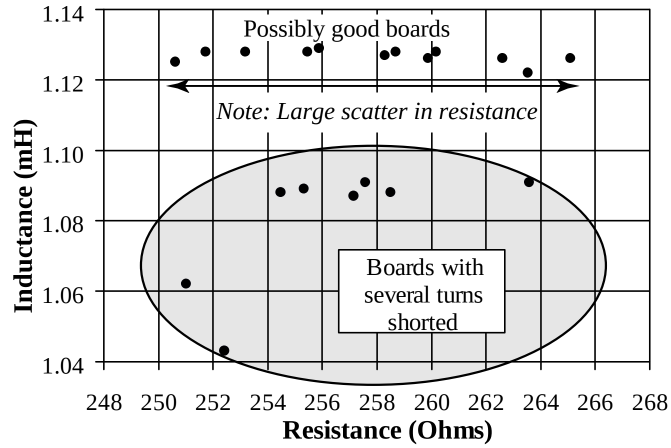

Fig. 2. Scatter plot of resistance and inductance measurements of 20 printed circuits for the GSI coil.

To inspect the probes in a ramped magnetic field, the probes were mounted side-by-side on a flat plate and placed in a large-aperture dipole. The dipole was ramped at ~ 0.1 T/s for several seconds and the signal from each of the windings was recorded. Fig. 3 shows the results for four Biomed probes – two good ones, one with a single shorted turn, and one with a shorted layer. Inductance measurements on the same boards were in qualitative agreement with these results, but were not accurate enough to allow a precise matching of probe area. For example, coil-4 shows a 1.75% reduction in the probe area from the field measurements, corresponding to a single shorted turn, but shows a 3.2% reduction in inductance. Similarly, field measurements show a reduction of 8.2% in the area of coil-3, but the inductance measurements show a drop of 14.6%. Nevertheless, the inductance measurements being much simpler to perform, we have adopted these measurements as the basis for a quick inspection. The boards that appear matched in inductance will then be further tested in a ramping magnetic field for a more precise matching of the total surface area.

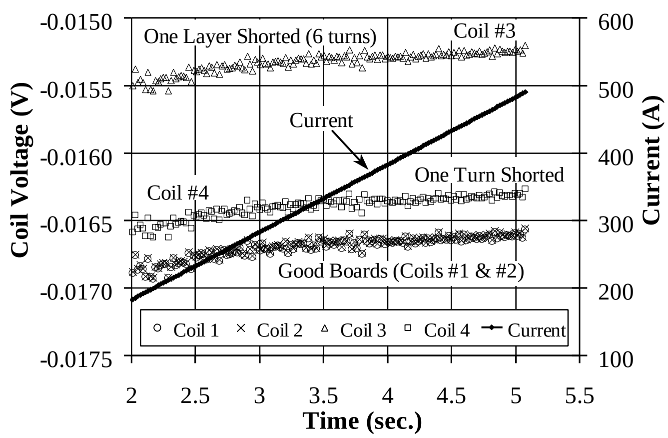

Fig. 3. Plot of the voltage generated versus time in four non-rotating Biomed probes in a ramping dipole field. The plot also shows the magnet current versus time.

We have inspected 40 probes so far, and have found 10 of them to be defective. It has been possible to repair only a few of them where the shorts were in the outermost layers. The problems found with the probes are similar to those found in an earlier use of printed circuits to measure magnetic fields [8].

B. Probe Calibration

The probes were calibrated by rotating the probe array in a constant dipole field, recording the output simultaneously and analyzing the data with an FFT. Fig. 4 shows the outputs. The high-frequency variation seen in each signal is due to vibrations of the rotating coil. Since the frequency of the vibration is much larger than that of the coil rotation, it does not affect the lowest (dipole) term of the FFT, which is used for calibration. The coil bearings are being modified to reduce the vibration. It should be noted that for fast measurements, the probe will be used in a stationary mode and the vibration is not a problem.

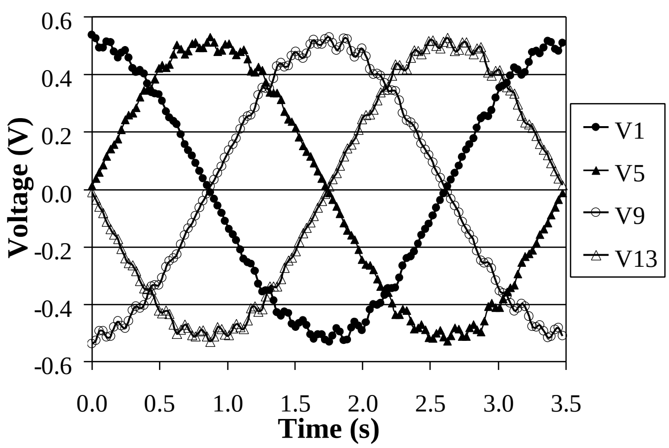

Fig. 4. Plot of the voltages generated by some of the 16 Biomed probes mounted on a support cylinder that rotates with a period of 3.5 s in a constant dipole field of 1.37 T. The signal amplitude corresponds to a ramp rate of 2.46 T/s in the stationary mode.

Fig. 5 shows the calibration results for 16 probes. The difference between the maximum and the minimum responses is nearly 0.06%, somewhat larger than desired for a simplified analysis method. To reduce the spread in probe responses, additional probes have been ordered. Since the probes are inexpensive, sorting will be used to obtain the desired uniformity of response, preferably with a standard deviation of ~0.01%. The phases of the dipole signals are used to calibrate the angular positions of the various windings.

IV. DATA ACQUISITION SYSTEM

To minimize the cost of the data acquisition system, we purchased digital multimeters with the required measurement accuracy but a minimum of extra capability (HP 34401). However, these meters do not allow sufficient control of the time of the trigger for measurements. The variation of the timing leads to inaccurate measurements of fast-changing signals. This can be seen in Fig. 6, which displays the signals recorded with the same 10 V, 4 Hz sin wave input to all the meters and the difference between two of them, ~ 10 mV. (For this measurement, the display was turned off to minimize the variation in trigger time.)

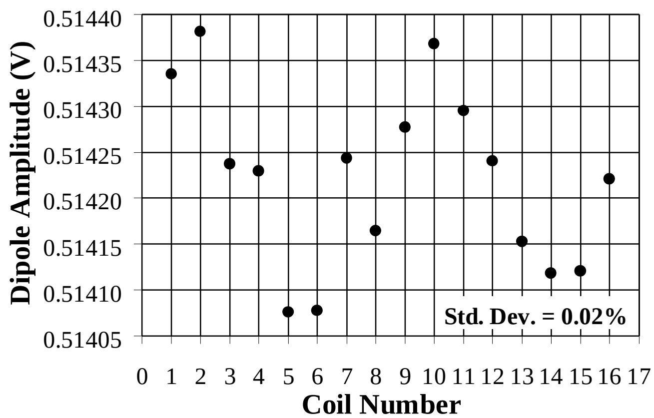

Fig. 5. Dipole amplitudes from the FFT of the 16 rotating probe voltages in a fixed dipole field of 1.37 T.

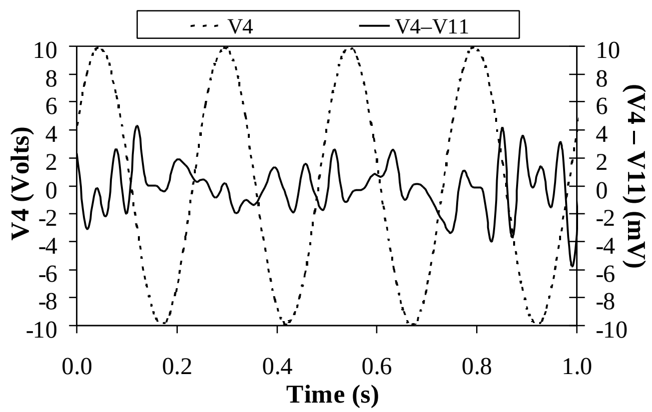

Fig. 6. Voltage input to each of the multimeters and recorded by one of them (left ordinate) and typical voltage difference between two of them (right ordinate) versus time.

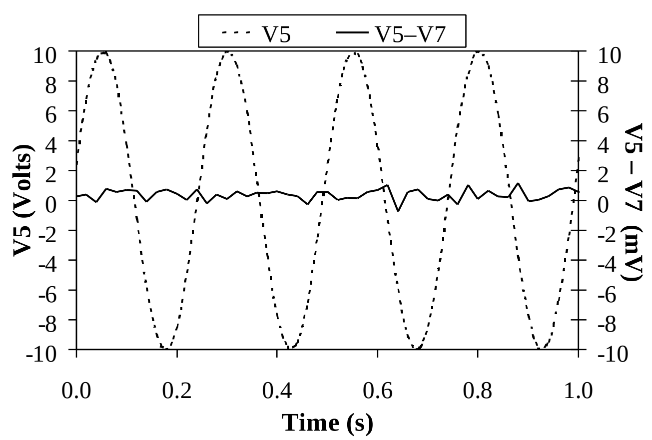

Fig. 7. Voltage input to each of the ADC's and recorded by one of them (left ordinate) and typical voltage difference between two of them (right ordinate) versus time.

Our present plan is to use an array of 16-bit ADC's and build programmable gain amplifiers in order to obtain the factor of ~ 100 gain needed for some of the measurements. Fig. 7 shows the results of an ADC measurement of the same signal as that shown in Fig. 6. With improved timing, the variation between ADC channels is ~ 1 mV.

The programmable gain amplifiers are under construction. For stability, they will be mounted in a temperature-controlled environment. The system will be designed so that a calibration run will precede every data acquisition run. A test of the complete system is planned for later this year.

V. DATA ANALYSIS

For the purpose of data analysis, a coordinate system internal to the coil is used. The X-axis is chosen along the centerline of one of the probes, as shown in Fig. 8. Since the relative angles of all the probes are determined by rotating the coil in a dipole field, the angular positions, θ_i, of all the probes are known in this coordinate system. In practice, it is desirable to align this coordinate system as best as possible with the magnet's principle axes. A perfect alignment, however, is not essential, and will not be assumed in the data analysis.

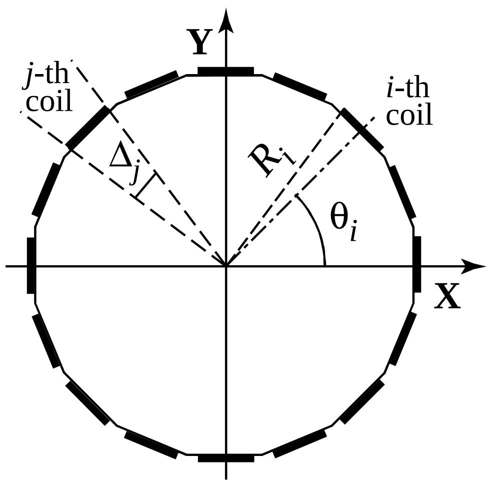

Fig. 8. Coordinate system used for analysis of data in the stationary mode.

The flux linked at time t through the i-th tangential coil of length L_i and having N_i turns is given by

$$\Phi_i(t) = \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left(\frac{R_i}{R_{ref}}\right)^n \sin\left(\frac{n\Delta_i}{2}\right) \times \left[B_n(t)\sin(n\theta_i) + A_n(t)\cos(n\theta_i)\right] \quad (1)$$

where $B_n(t)$ and $A_n(t)$ are the normal and skew $2n$-pole terms respectively at a reference radius of R_{ref} in a harmonic expansion of the 2-D field components. The induced voltage in the i-th probe in the stationary mode results from a time variation of the field components, and is given by

$$V_i(t) = \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left(\frac{R_i}{R_{ref}}\right)^n \sin\left(\frac{n\Delta_i}{2}\right) \times \left[\dot{B}_n(t)\sin(n\theta_i) + \dot{A}_n(t)\cos(n\theta_i)\right] \quad (2)$$

where the dot over B_n and A_n denotes time derivative. In a conventional rotating tangential coil, a complete angular profile is obtained by rotating the *same* coil. All the geometric parameters in this case are angle independent, and the expression for the flux, or the voltage, represents a Fourier series. In the case of an array of tangential coils in the stationary mode, the geometric parameters are not necessarily the same for all the coils. Consequently, the various terms in the summation in (1) or (2) are *not* the same as the Fourier components of the voltage profile. Thus, a simple FFT analysis of the voltage profile assembled from the signals of all the probes does not directly give the harmonic terms.

If the geometric parameters of all the probes are nearly the same, and if the angular positions of the probes are uniformly spaced, one can apply a simple FFT analysis. Thus, it is very important to precisely match the characteristics of all the probes, not only in the fabrication of the printed circuit boards, but also in their mounting on the coil form. If this condition cannot be met, one must obtain the time derivatives of various harmonics using a fitting procedure. We plan to carry out the analysis using both approaches to check the adequacy of the FFT technique for a given coil.

The harmonic components at any time are obtained by integrating the time derivatives:

$$B_n(t) = B_n(0) + \int_0^t \dot{B}_n(t)\,dt; \quad A_n(t) = A_n(0) + \int_0^t \dot{A}_n(t)\,dt \quad (3)$$

The initial values of the harmonics, $B_n(0)$ and $A_n(0)$, can be determined, for example, using the same coil in a rotating mode before the magnet is ramped. The numerical integration can be avoided by using digital integrators instead of voltmeters to record the probe signals.

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